Spacecraft Design, Development and Operations in Just Five Hours per Week: Experience from the USAF Academy *FalconSAT* Program

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Abstract

The paper describes overall experience and lessons learned from the USAF Academy’s small satellite research program—“*FalconSAT*”—and the challenges faced by undertaking serious space mission development in a highly-constrained undergraduate environment. The goal of the program is to give students the opportunity to “learn space by doing space.” Background on the program is first presented including successes and failures since the program’s inception. Discussion begins by focusing on specific curriculum changes made within the Academy Department of Astronautics over the last several years to enable students to have even 5 hours per week to devote to space mission development. The culmination of this curriculum is a capstone small satellite design course sequence. The processes within these courses will be described along with how the courses are organized to get the maximum amount of learning and effort out of the students given the limited class time available. Various aspects of the courses will be discussed such as the Design Review Process and how cooperation with other departments and organizations help to provide expertise and extra funding. Challenges associated with these courses and the associated project that the students are expected to complete are also discussed. How are student learning objectives and real world deadlines balanced? How is the problem of high student turn-around handled? The paper will discuss various solutions the Academy has evolved to address these challenges. The paper concludes with current program status and recent feedback from students involved in the project.

I. Introduction

The capstone of the United States Air Force Academy’s Department of Astronautics Small Satellite curriculum is the *FalconSAT* Program. One goal of the program, housed within the Academy’s Small Satellite Research Center, is to give undergraduate cadets the unique opportunity to “learn space by doing space.” The program facilitates cadet development of small satellite mission design through instructor guidance and mentorship. It allows cadets to gain real-world experience with satellite design,
assembly, integration, testing, and operations within the context of a two-semester engineering course sequence.

A second goal of the program is to provide a useful nanosatellite platform for Air Force and Department of Defense (DoD) space experiments. Through *FalconSAT* participation, cadets are given a hands-on opportunity to apply the tools developed in a classroom to a real program, ideally preparing them for the situations they may encounter as officers and as engineers after they graduate.

This paper will describe some of the experiences and lessons learned from the USAF Academy’s small satellite research program—“*FalconSAT*”—and the challenges faced by undertaking serious space mission development in a highly-constrained undergraduate environment. Background on the program is first presented including successes and failures since the program’s inception. Discussion begins by focusing on specific curriculum changes made within the Department of Astronautics over the last several years to enable students to have even five hours per week to devote to space mission development. The culmination of this curriculum is a capstone small satellite design course sequence. The processes within these courses will be described along with how the courses are organized to get the maximum amount of learning and effort out of the students given the limited class time available.

Various aspects of the courses will be discussed such as the Design Review Process and how cooperation with other departments and organizations help to provide expertise and extra funding. Challenges associated with these courses and the associated project that the students are expected to complete are also discussed. How are student learning objectives and real world deadlines balanced? How is the problem of high student turn-around handled? The paper will discuss various solutions the Department of Astronautics has evolved to address these challenges. The paper concludes with current program status and recent feedback from students involved in the project.

### II. Discussion

The USAF Academy’s foray into small satellites began with a series of cadet-built prototypes that were “launched” on high altitude balloons. These projects gave the students immediate, hands-on experience and allowed the Department of Astronautics to gradually evolve the curriculum to accommodate increasingly more ambitious space projects. This initial development culminated in the launch of *FalconGold* in October 1997. *FalconGold* was a fixed, secondary payload on an Atlas-Centaur launch vehicle.

The mission of *FalconGold* was to determine whether GPS signals could be detected above the GPS constellation. *FalconGold* relayed GPS data for 15 days prior to battery depletion. Successful operations and data recovery from *FalconGold* concluded that GPS signals could be used for orbit determination, even beyond the altitude of the GPS constellation. [1]

The Academy’s first “free flyer” satellite, *FalconSAT-1*, was launched on January 14, 2000 aboard the first *Minotaur* launch vehicle (a modified Minuteman II ICBM) along
with several other university-built microsatellites. *FalconSAT-1* flew the DoD-supported Charging Hazards and Wake Studies—Long Duration (CHAWS-LD) experiment which was designed to measure electric potential created by a spacecraft’s wake. CHAWS-LD examined how spacecraft charging varies throughout an orbit. The CHAWS-LD sensor was designed to assess the hazards for spacecraft operations in the wake of larger bodies. Unfortunately, a power system problem became apparent soon after deployment. Despite repeated attempts to recover the spacecraft by the cadet/faculty operations team, the mission was declared a loss after only one month.

Although it was considered a technical failure, *FalconSAT-1* represented an academic success for the program as cadets participated from “cradle to grave” in a real-world mission with an all too real-world outcome. Cadets designed and built *FalconSAT-1*’s payload and subsystems, and they were integral in the mission operations from devising operations plans to participating in the launch campaign. Cadets also manned the Academy’s ground station during overhead passes of a satellite not operating under nominal conditions. Cadets involved with trouble-shooting the anomalies soon after deployment certainly gained deep insight into system functions and operations.

Table 1 summarizes the various milestones in the Academy’s Small Satellite program thus far. The current project, *FalconSAT-2*, is the third satellite to be developed within the Academy’s Small Satellite program. Details of this satellite will be discussed later in the paper.

<table>
<thead>
<tr>
<th>DATE</th>
<th>EVENT</th>
<th>SATELLITE</th>
<th>MISSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 1995</td>
<td>Balloon flight</td>
<td>USAFASAT-B</td>
<td>Attitude Control Demonstrator</td>
</tr>
<tr>
<td>Mar 1996</td>
<td>Balloon flight</td>
<td>Glacier</td>
<td>GPS &amp; Magnetometer Experiment</td>
</tr>
<tr>
<td>Sep 1996</td>
<td>Balloon flight</td>
<td>PHOENIX</td>
<td>Laser Communication Demo</td>
</tr>
<tr>
<td>Apr 1997</td>
<td>Balloon flight</td>
<td>FalconGold</td>
<td>GPS Signal Capture</td>
</tr>
<tr>
<td>Oct 1997</td>
<td>Space launch</td>
<td>FalconGold</td>
<td>GPS Signal Capture</td>
</tr>
<tr>
<td>Jan 2000</td>
<td>Space launch</td>
<td>FalconSAT-1</td>
<td>CHAWS-LD</td>
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</table>

To achieve the goal of giving all Astronautics Majors at the Academy the opportunity to gain hands-on satellite building experience, the Department of Astronautics had to make major changes to the curriculum and course sequences within the major. Table 2 displays the old and new course sequence for the Small Satellite curriculum of the Astronautics Major. In addition to these courses, cadets in the Astronautics Major take courses in Rocket Propulsion, Astrodynamics/Orbital Mechanics, and Control Systems to complete their degree.
Table 2. Small Satellite Astronautics Major Course Sequences.

<table>
<thead>
<tr>
<th>OLD COURSE SEQUENCE</th>
<th>NEW COURSE SEQUENCE</th>
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<tbody>
<tr>
<td>3rd Year:</td>
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<tr>
<td>Astro 331: Intro to Spacecraft Design</td>
<td>3rd Year:</td>
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<tr>
<td></td>
<td>Astro 331: Space Vehicle Design I</td>
</tr>
<tr>
<td></td>
<td>Astro 332: Space Vehicle Design II</td>
</tr>
<tr>
<td>4th Year:</td>
<td>4th Year:</td>
</tr>
<tr>
<td>Astro 436: Spacecraft Analysis &amp; Design I</td>
<td>Engineering 433: Small Spacecraft Eng I</td>
</tr>
<tr>
<td>Astro 433: Spacecraft Analysis &amp; Design II</td>
<td>Engineering 434: Small Spacecraft Eng II</td>
</tr>
</tbody>
</table>

From Table 2, in this old sequence students were introduced to spacecraft design in their 3rd year in Astro 331. This was a pure design course where they completed a paper study of a particular mission. The capstone sequences of their 4th year included a lecture-based course, Astro 436, on spacecraft analysis and design and a second course, Astro 433, that gave students the opportunity to design, build, and launch a small model rocket.

To create the large block of time needed to do serious spacecraft design, development and operations, and give the students the academic tools they need to tackle these far more difficult real-world problems, the Department of Astronautics implemented major curriculum changes. To begin with, much of the content of the old Astro 436 course which focused on spacecraft subsystem requirements and analysis was shifted into a two-course sequence, Astro 331 and Astro 332, in the 3rd year. In addition, a variety of labs were created to give students early, hands-on experience in electronic subsystems, power subsystems, communications subsystems, and attitude control subsystems. This change set the stage for a new two-semester course sequence in the 4th year, Engr 433 and Engr 434, in which students could finally step up to the challenge of actually designing, building and operating a real-world spacecraft.

Note that the course designation for the senior-level spacecraft design course was changed from “Astro” for Astronautics to “Engr” for Engineering, highlighting the interdisciplinary nature of spacecraft design. This represented another change in the focus of the program as a concerted effort was made to involve cadets from a variety of departments, not just Astronautical Engineering, to expand the knowledge-base of participants and give every cadet, regardless of their major, an opportunity to contribute to the program. This approach better reflects how technical programs in the Air Force are conducted, involving engineers, scientists, managers, technical writers and other experts from a variety of fields.

The greatest success in this goal of interdepartmental cooperation has been with the USAF Academy’s Department of Physics. Teaming scientists who have keen interest in designing space experiments with engineers who want to build missions has provided great synergy to the program. The CHAWS-LD experiment, flown on FalconSAT-1, was conceived and built by faculty and students from the USAF Academy’s Department of Physics. This has not only given an interesting scientific focus to the missions, but has brought real-world credibility as these experiments. The experiments have competed for recognition across the DoD to be officially approved by the DoD Space Experiments

Review Board. This gives the added bonus of critical additional funding, and all-important space launch opportunities.

With this real-world focus, real-world funding and real-world visibility, it has become ever more important to run the program using real-world tools. Chief among these are rigorous systems engineering processes including technical reviews. The DoD mandates a tailored acquisition sequence for all its programs that closely follows the IEEE Standard for Application and Management of the Systems Engineering Process [2]. This process begins with requirements analysis and culminates in system deployment. Along the way, major milestones in the form of formal technical reviews are conducted. These include, among others:

- System Requirements Review
- Concept Design Review
- Preliminary Design Review
- Critical Design Review
- Test Readiness Review

By its nature, any design class is open ended and difficult to program lesson-by-lesson as a traditional lecture-based course would be. However, by requiring students to follow prescribed, industry-standard systems engineering processes, some formal structure can be imposed on the semester and the design reviews serve as major deliverables for grading purposes.

Even with two space launches under its belt, the FalconSAT program is still growing and evolving. The on-orbit failure of FalconSAT-1 prompted a critical review of the program and an assessment of lessons learned and the challenges faced. What the cadets/faculty learned was that the program could do better at:

- Establishing the configuration envelop early
- Building and testing breadboard hardware
- Responding to externally imposed schedules
- Engineering documentation
- Getting cadets more involved with assembly, integration and testing
- Thermal modeling

From these lessons, cadets/faculty developed the following specific recommendations:

- Constrain the design envelop (buy-in pre-integrated subsystems)
- Don’t commit to unrealistic launch schedules
- Spread out faculty workload

In addition, the program still faces several major, inherent challenges. These include:

- Limited contact time—Even with a double-hour class, students are only available an average of five hours per week. Unlike a normal university or
graduate school, cadets at the USAF Academy have 95% of their time scheduled for them, giving them very little flexibility to devote additional time to the program even if they want to.

• 100% turn-over each year—The USAF Academy is an undergraduate institution only, thus each year we lose our seniors to their careers in the Air Force and can’t keep them around as graduate students to continue working on the program. Each year cadets must climb the learning curve all over again with a new crop of seniors.

• Balancing academic vs. real world schedules and requirements—The program receives funding from outside Air Force agencies including the Air Force Office of Scientific Research (AFOSR) and the Space & Missile Center/Space Test Program (SMC/STP). While both of these agencies are 100% supportive of the academic goals of the program, the Academy must still respond to their needs and expectations.

• Documentation!—This, of course, is a challenge to any engineering design program. However, this problem is made even more critical by the 100% turn-over the program faces each year. The program has taken one approach to this problem by shifting from “document-based” design to “model-based” design. This is described more fully in a separate paper.[3]

Being launch schedule driven, *FalconSAT-1* proceeded directly to a proto-flight model, without first building engineering models or development tools. While this “faster, better, cheaper” approach can be effective, it has proven lacking within an academic environment, especially as the program turned to the next mission—*FalconSAT-2*. The lessons learned from *FalconSAT-1* have motivated significant structural change to the program, with the intention of building a program first and a satellite second. Thus, the new approach has been to focus on building up infrastructure, including design and development tools that can serve as a firm foundation to allow the design to evolve steadily over the course of several missions. The *FalconSAT-2* design effort is aimed at developing a flexible platform that can be readily adapted and enhanced to meet future payload requirements and secondary launch opportunities.

Specific to this new approach has been a major effort to bound the problem faced by the students. To do this, the program has leveraged research at the Surrey Space Center at the University of Surrey, UK. In June 2000, engineers from Surrey Space Center launched the first SNAPSat satellite. This satellite was a 6.5 kg, highly functional, spacecraft with five imaging cameras, 3-axis attitude control and a propulsion system.[4] SNAPSat represents the culmination of research into open spacecraft architectures. By buying in to this SNAPSat architecture, the Academy program has achieved an “out of the box” solution for several critical subsystems; including power, communications and, most important, data handling.

Using one set of SNAP hardware, the *FalconSAT* Avionics Simulation Testbed (FAST) was established in Fall 2000. FAST provides both a long-term facility for cadets to gain hands-on experience with spacecraft hardware and software, as well as overall program
risk reduction by providing a facility for subsystem, software, and operational procedures development and testing. Figure 1 shows cadets working on FAST in the Academy’s clean room. While the use of the SNAP hardware has eased the design problem in many respects, considerable effort still remains in the areas of payload design and development, structures, attitude control, thermal control, solar panels, testing and operations—more than enough to challenge even the most ambitious undergraduate students.

![Figure 1: Cadets in USAF Academy Clean Room](image1)

### III. Current Status

As of this writing, students in Engr 433 in Fall 2000 completed implementation of FAST and initial development of flight software and procedures. The primary payload for *FalconSAT-2* is the Micro-Electro Static Analyzer (MESA). MESA is designed to detect and characterize plasma bubbles in the ionosphere which can interfere with Global Positioning System (GPS) signals and other military-critical communications. A photograph of the MESA sensor is shown in Figure 2. During Engr 434 in Spring 2001, students will finish designing, then build and test an engineering model of *FalconSAT-2*. In addition, during this semester, for the first time Engr 434 will begin to interface with 3rd year students in Astro 332, giving them a early look into the program and helping to jump start their participation in Fall 2001 when they will have the challenge of building and testing a qualification and later the actual flight model of *FalconSAT-2*. Launch of *FalconSAT-2* is planned for late 2002 on the Space Shuttle.

![Figure 2: Photograph of MESA Sensor](image2)
IV. Conclusions

While positive progress on the systems engineering side of the problem is important, the most critical measure of program success is how well the program achieves its academic goals. The basic philosophy that initiated the Academy’s small satellite program in the first place was a belief that students learn far more by building, testing and doing than by lecturing and exams. While it’s always difficult to assess the long-term efficiency of any curriculum changes, initial student feedback is extremely positive. Students have responded very well to a class based on real-world problems. In fact, their primary frustrations have been those that all engineers must face after graduation. One concern of going to purely design-based classes as opposed to additional lectures was that there would be a de-emphasis on depth in favor of breadth. However, this has not been the case. Each student has a particular subsystem specialty that requires far more depth than a survey course would expose them to. Furthermore, they receive a broad appreciation for how their subsystem fits into the overall design picture.

To a large extent, the jury is still out on the overall success of the program. The most important measure is how well this program prepares cadets for their jobs as engineers, pilots and program managers in the Air Force. It will be several years before this long-term feedback can be received and assessed. However, one recent student’s feedback provides significant encouragement that the program is on the right path.

“The FalconSAT program has allowed me to apply the knowledge from traditional classroom courses in a way that ordinary projects and paper designs cannot. I have learned more about leadership, management, and the systems engineering process than could ever be learned in the classroom.”

- USAF Academy SmallSat student

With this type of encouraging feedback, the program is continuing to evolve and expand to meet the needs of an increasingly technical and space-orientated Air Force.

Bibliography


Biographies

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Jerry Jon Sellers is an active duty Lieutenant Colonel in the U.S. Air Force. His work experience includes: Guidance & On-board Navigation Officer, Space Shuttle Mission Control Center, NASA, Johnson Space Center, Houston, Texas; Assistant Professor of Astronautics at the USAF Academy; and Chief, Astronautics for the Air Force European Office of Aerospace Research & Development, London, UK. His educational background includes a BS in Human Factors Engineering from the USAF Academy, an MS in Physical Science/Astrodynamics from the University of Houston, Clear Lake, an MS in Aeronautics/Astronautics from Stanford University and a Ph.D. in Satellite Engineering from the University of Surrey, UK. Currently he is the Director of the USAF Academy Small Satellite Research Center in Colorado Springs, Colorado.

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